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THE VARIATION OF THE ANGLE OF INTERNAL FRICTION WITH SIZE CONSIST FOR MECHANICALLY-CHIPPED MATERIAL - YEAR TWO

Donald E. Raab, et al

Pennsylvania State University

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The Variation of the Angle of Internal Friction with Size Consist for Mechanically Chipped Material — Year Two

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13. ABSTRACT

In order to improve aspects of materials handling in the rapid excavation process, research is underway to characterize the muck from mechanical tunnel boring machines. The specific project involves the correlation of the angle of internal friction, ϕ, to the size consist, often termed gradation, of this mechanically-chipped material. Existing references demonstrate that this angle depends upon mineral type, and for a given mineral type upon size of particles. Particle shape is usually a function of mineralogical character and is not as important a parameter in influencing this angle. Seven samples collected from tunnels located throughout the U. S. have been analyzed for gradation, and the angle of internal friction using a triaxial test. The results not previously reported are presented here.

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I-C

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Technical Report Summary

Continued testing of materials gathered from tunnels bored by tunneling machines show some trends in the variation of the angle of internal friction with variations in particle size. Triaxial tests have been completed on muck samples gathered from seven different tunnels. The particle sizes tested include the "combined" sample, as received from each tunnel, also the 6-mesh, 40-mesh, and 140-mesh fractions. Indications are that for cohesionless materials, the angle of internal friction (ϕ) increases with a decrease in particle size for triaxial tests performed under drained conditions. Cohesive materials lose strength when saturated and show a very low angle of internal friction.

New samples have been collected from three tunnels. At one tunnel, five samples were collected under variations in machine thrust and cutter head speed. Preliminary sieve analysis of these samples shown a slight variation in size consist due to machine variations.

No major delays have been encountered, nor are any anticipated. Additionally, no new major purchases are necessary.

I. INTRODUCTION

Progress of the Project

The purpose of the project and problems reached have been discussed in previous reports[6,7,8]. Since the May 6, 1972, Annual Report[8], all of the remaining samples collected on the year I sample-gathering trip have been tested in the triaxial cell. After four tests of a given sample of a particular size have been performed, a series of Mohr's Circles is drawn and the angle of internal friction (ϕ) is measured[2,3,8]. This angle ϕ is analyzed and compared with ϕ's from all previous and succeeding tests. Results and comments on these analyses appear later in this report.

During this past summer, an additional sample-gathering trip was taken. One thousand, three hundred pounds of samples were collected on that trip, in addition to 100 pounds collected on another short trip taken in September. Some of these samples have been sieved. Sieve analysis results will also be presented later in this report.

Scope of the Report

This report will justify the collection of new samples, present and discuss test results from the remaining year I samples, offer sieve analyses of the new samples, and draw conclusions and suggest future plans. Final conclusions concerning the tests and results will, of course, not be drawn before all testing is complete. Anomalous test results can often be explained only after many more tests of the same nature have been performed.

All of the results presented in the body of the report are supported by data in the Appendices. As in the Annual Report[8], all of the Mohr's Circles and sieve analysis curves are included. Also included is a diary of sample collection, data sheets for each tunnel of technical information for each tunnel sampled, and a tabulation of Mohr's Circles Data.

II. COLLECTION OF NEW SPECIMENS

Purpose of Collection

All of the muck samples gathered during the Summer of 1971 sample-gathering trip have been completely tested. Sieve analyses have been performed, and triaxial tests of the combined sample and three individual size fractions have all been completed. The next step in the research is to determine the variation of ϕ with variations in size consist.

It would be possible to mix samples on hand to achieve desired consists, however, this procedure could very well introduce errors. First of all, the samples on hand have all been tested at least once in the triaxial cell. Re-use of this material could possibly distort results. Secondly, it would not be useful to mix a consist that could not realistically be generated by a tunneling machine. Consequently, it was decided to collect more samples.

Samples Acquired

The intention of the second trip was to spend several days at a few of the most promising tunnel sites in order to obtain a variety of samples under variations in machine parameters. Although most tunneling machines can vary their cutter head thrust, only the D.C. machines can also vary their cutter-head rotation speed. Since the Farmington tunnel was the only previously visited tunnel with a D.C. powered machine, another trip was made to that tunnel. By varying the cutter-head speed and thrust, it was hoped that a machine-generated variation in size consist could be obtained. Five samples were obtained (see Appendix I) under variations in machine parameters. The variations are shown in Table I.

Table I

Operating Parameters of Navajo Tunnel Machine for Specimen Collection

1.	1,090,000 lb. thrust	8 RPM
2.	850,000 lb. thrust	8 RPM
3.	612,000 lb. thrust	8 RPM
4.	1,090,000 lb. thrust	7 RPM
5.	1,090,000 lb. thrust	5 RPM

The samples from the Nast tunnel, collected on the first year's trip, behaved well during triaxial testing. This was probably due to the non-cohesive, competent, granitic rock that composed the sample. For this reason, the Nast tunnel was visited on the return trip from Farmington. The hope was to collect several samples under variations in machine thrust. Unfortunately, the machine was down during our visit as is explained in Appendix I. No samples could be taken.

White Pine, Michigan, was the location of the last tunnel visited on the summer trip. Here again, it was hoped that samples generated under various machine thrusts might be collected. The machine at White Pine was also down during our visit (Appendix I), so this was not possible. A sample was obtained from the stock-pile outside, however.

Later in the year, a trip was made to the Moss Point Drainage System near Cleveland, Ohio. Two machines were in operation at the time, but only one was a hard-rock borer as is discussed in Appendix I. A 150-lb. sample was taken from the conveyer belt of the hard-rock tunneler and brought back to the laboratory. The sample is a shale which may cause problems in testing, as have other shales previously tested. However, it is a good quantity of fresh sample which may prove useful later in the project year.

III. LABORATORY TESTING

Triaxial Tests

The four remaining tunnel samples on which tests were performed are the Nast, Chicago, White Pine, and Toronto. Some repeat tests were run on the Farmington material in an effort to obtain more consistent results. Test results for all seven tunnels are shown in Table II for comparison purposes. Mohr's Circles for each set of tests appears in Appendix III, and Appendix IV tabulates the confining pressures and failure loads for each test.

Problems and Observations

A major problem in testing the larger materials (> 40 mesh) had previously been that of membrane puncture. This problem has been adequately resolved at this point. Consequently, the particle sizes tested for each tunnel are the combined 6 mesh, 40 mesh, and 140 mesh. Before the membrane problem was solved, it was impossible to test the 6-mesh materials without puncturing membranes. For this reason, the 6 mesh test results are missing from some of the samples tested during the first year of research.

During the first year of testing, all membranes supplied by Soiltest were .0012 inches in thickness, regardless of cell size. This thickness was sufficient for testing 40-mesh and 140-mesh material in the 1.4-inch cell. However, testing of the 6-mesh material and larger caused puncture, regardless of cell size. An attempt at using multiple membranes met with limited success. To be completely successful, it was determined that eight to ten

Table II

Tabulated Angles of Internal Friction

	Philadelphia	Farmington	Heber City	Nast	Chicago	Toronto	White Pine
Combined	28.5°	30.0°	0°	37.0°	38.0°	21.5°	33.0°
#6 mesh*	29.0°	-----	-----	27.0°	27.5°	27.5°	29.5°
#12 mesh*	-----	-----	22.0°	-----	-----	-----	-----
#40 mesh	32.0°	38.0°	0°	28.0°	31.5°	0°	27.4°
#140 mesh	34.5°	32.0°	0°	29.0°	32.0°	0°	24.5°

*6 mesh was the desired size fraction, 12 mesh was tested once in an attempt to resolve puncture problems membranes, one superimposed upon the other, would be needed in each test of 6-mesh material at 60 psi confining pressure in order to stop leakage completely. Due to the inefficiency and impracticality of multiple membrane usage, the possibility of using thicker membranes was investigated. Several manufacturers were contacted before it was decided to order the thicker membrane from Testlab of Chicago, Illinois.

For the 1.4-ich and 2.8-inch cells, membranes of .0025 inches in thickness were ordered. For the 6-inch cell, membranes of .0025 and .0050 inches in thickness were ordered. The 6-mesh material can be tested in the 1.4-inch cell without exceeding the limit of particle size being less than or equal to 1/6 the diameter of the cell[4]. Tests of 6-mesh material in the 1.4-inch cell under 60 psi confining pressure did not experience leakage when the .0025-inch thick membranes were used. Additionally, tests of 6-mesh material in the 2.8-inch cell under 60 psi confining pressure did not result in membrane leakage when the .0025-inch thick membranes were used.

A 6-inch test on some playing marbles was tried using the .0025-inch thick membranes. Marbles were used in order to prevent contamination of a large quantity of sample should the membrane puncture. The membrane did puncture at 60 psi confining pressure, so the .0050-inch thick membrane was tried. This time the membrane did not puncture at 60 psi confining pressure.
After having made many tests of combined material samples in the 6-inch cell, the best procedure seems to be to use a .0050-inch

thick membrane with a .0012-inch thick membrane superimposed over it. No membrane puncture or glycerin leakage into the sample has been detected when this procedure is followed.

The next question that comes to mind is do thicker membranes add to the strength of the samples being tested? If a 6-inch test is being run, the use of two membranes would increase the total effective diameter of the sample to 6.0000 + 2 (0.0050 + 0.0012) = 6.0124 inches. This could add some apparent strength to samples being tested under very high confining pressures, but it is thought that this added strength is negligible under confining pressures of 15, 30, 45, and 60 psi. This assumption is also reinforced by Marachi who tested at somewhat higher confining pressures[4].

Looking at Table II, it can be seen that for the Philadelphia, Nast, and Chicago tunnels, the angle of internal friction generally increased with a decrease in particle size. This was not the case for the other three tunnels. The reason for the unusual results obtained from the Farmington material is still not fully understood. Many additional tests have been run on the Farmington material, yeilding mostly non-reproducible results. Whether or not the fact that the Farmington material is a weak sandstone with some shale has anything to do with this non-reproducibility is unclear.

The mineralogy of the Philadelphia, Nast, and Chicago materials probably explain their consistent results. All three were composed of fairly competent rock which produces a cohesionless-bulk material when crushed. The Heber City, Toronto, and White Pine samples were all clays or shales, which create difficulties in a saturated triaxial test. In all three, the angle of internal friction was considerably lower in the smaller particle size ranges than in the larger. The small particle size samples evidently lose their strength when tested under saturated conditions. No doubt, the presence of water lubricates the clay particles and causes cohesive behavior.

Sieve Analysis of New Specimens

Sieve analyses have been performed on all samples collected on the second summer sample-gathering trip. This includes the five samples from the Farmington tunnel and the sample from the White Pine tunnel. To date, a sieve analysis has not been performed on the material gathered at the tunnel in Euclid, Ohio. Gradation curves for the samples appear in Appendix V of this report. One of the plots shows a composite of all five of the Farmington samples for comparison purposes. Although a detailed statistical analysis of these curves is not available at this time, it appears from the composite graph that machine variations do not drastically affect the size consist of the muck. It also appears that the degree to which the size consist is affected depends more on cutter head rotation speed than thrust against the face.

The composite graph of the White Pine I and White Pine II gradation curves also show similar trends. This is an interesting point since there is a variation in rock type between the two samples. The machine parameters did not change.

Once the new samples had been sieved for size, the remaining samples were coned and quartered[1] down to sizes which could be conveniently tested. All of the material was passed through a 1-inch sieve according to the contract proposals[5,7]. The purpose is to maintain the proper 1/6 ratio of maximum particle size to cell diameter. These samples are now ready for testing in the 6-inch cell.

IV. CONCLUSIONS AND FUTURE PLANS

Conclusions drawn in previous reports[8] are somewhat more strengthened by the triaxial test results given here. Generally speaking, the angle of internal friction increases with a decrease in particle size for saturated cohesionless granular material. It appears that the combined samples have the highest angle of internal friction. For saturated cohesive clay materials, strength has been found to decrease with a decrease in size. The angle of internal friction quite often goes to 0° in the very small particle size ranges. The combined sample may show some strength if a large percentage of the sample consists of large particles (e.g., White Pine and Toronto), and may show no strength if a large percentage of the particles are small (e.g., Heber City).

Tests have been conducted in an effort to determine the effect of cell size on ϕ. In Appendix III, Mohr's Circles appear for 6-mesh material run in both 1.4-inch and 2.8-inch cells. The tunnel samples used in this tangential study were the Chicago, Toronto, and White Pine. The changes in the angle of internal friction due to cell size effects was found to be very small. Some failure loads were within 5% of failure loads at the same confining pressure in the other cell. It is concluded that, for all practical purposes, cell sizes can be used interchangeably, providing that maximum particle size remains less than some fraction of the cell diameter. According to Marachi[4], this fraction is one-sixth.

The sieve analyses of the new Farmington samples indicate that some change in size consist can be obtained by varying machine parameters. It appears that size consist variations are more dependent on cutter head speed than thrust. The degree to which the samples are different in consist will have to be determined by a statistical analysis.

It is hoped that one more very large quantity of sample (about 1000 pounds) might be obtained from a tunnel in competent granular material, such as a mica schist or granite. Hopefully, this sample will contain several variations in machine parameters, such as the Farmington material does. If it is discovered that no significant variationsin size consist can be obtained from variations in machine speed and thrust, then size consist variations might have to be mixed manually. Tests will be conducted on both this new material and the Farmington material, although the results from the Farmington material may be questionable. The friability of the material and the results of previous tests may make size consist testing of this material in the triaxial cell unrealistic.

Wetting agents are to be used in place of water as saturation fluid in order to examine the effect on the angle of internal friction. Fluid change tests will probably be run in the 2.8-inch cell in order to conserve on sample consumption and testing time.

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APPENDICES

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APPENDIX I

A DIARY OF SAMPLE COLLECTION

July 5, 1972

Navajo Irrigation Project

The details of the tunnel information and machine set-up are given in the October 20, 1971, semi-annual technical report[6]. Once again, our questions were answered by Mr. P. E. "Joe" Sperry. Mr. Sperry said that we had arrived just in time, since they were going to be holing through in the next day or two. We were taken underground by Mr. Jay Terry, the safety engineer, and Mr. Chuck Prior, the foreman. They cooperated completely with us, varying machine parameters just as we asked.

We had ten army surplus ammunition boxes with us, so we filled two boxes for each of the five samples we took. The first sample we took was at normal cutter head thrust and RPM. For the second and third samples, we asked them to maintain the RPM and reduce the thrust. For the fourth and fifth samples, the thrust was brought back to normal and the RPM was reduced. The thrust and RPM for the five samples is shown in Table I.

Mr. Prior explained that at greater than 8 RPM, centrifugal force prevents muck from falling on the conveyor belt readily. This causes re-cycling and re-grinding of the muck, which is undesirable. Consequently, no samples were taken at an RPM greater than 8. Additionally, the machine was operating on only three of its four thrust cylinders during our visit. One million, ninety thousand lbs. was, therefore, the maximum thrust we could achieve for a sample.

With the cooperation of Mr. Sperry, Mr. Terry, and Mr. Prior, all of the samples were collected within 45 minutes. The samples were shipped to State College via REA.

July 7, 1972

Fryingpan Project, Nast Tunnel

Upon arriving at the office of Peter Kiewit Sons, we were informed by Mr. Norm Tennock that the machine was down and would not be operating again for quite awhile. The machine was in a fault zone and had been damaged by boulders falling into the tunnel. The situation was so bad that it was decided to drill and shoot from an access adit back to the machine. The machine would then be walked up the tunnel to the face, and tunneling by mole would continue.

Button bits had been used on the mole, but plans were to go to a disc type with button inserts. Upon driving up to the tunnel site, we understood why button bits were being done away with. The muck on the stockpile was very fine and wet. Disc cutters would help to generate larger particles and perhaps save on energy and re-grinding. Due to the situation at Nast, no new samples could be taken. Again, details of the tunnel location, etc., can be found in the October 20, 1971, semi-annual technical report[6].

July 10, 1972

White Pine Copper

Our first contact at White Pine was with Mr. A. C. Bigley, Jr., Head of Metallurgical Research, since Dr. Cliff Hanninen of Mine Research was not in. Once again, we were told that the machine was down. The Robbins machine had been negotiating a curve and had reached a point beyond which the conveyor belt could no longer be used. A connection tunnel at this curve was being mined by drill and shoot. This connection tunnel would take care of the conveyor belt problem in addition to providing better ventilation. A two-hundred pound sample of the muck (the Nonesuch shale) was taken at the outside stockpile, however.

The next day, we met Bert Caverson of the Rock Mechanics section. He introduced us to one of his technicians who took us on a tour of the mine and showed us the Atlas-Copco machine, White Pine's second tunneling machine. The machine was explained to us by Clark Slay, who seemed very pleased with the operation and 700-feet-per-month advance rate of the machine. The only serious problem with the Atlas-Copco seems to be a materials handling one.

After visiting other parts of the mine, we were taken to the surface, and we departed. We brought the sample back to State College by automobile.

September 14, 1972

Moss Point Drainage System

This tunnel system is owned by the City of Euclid, Ohio, (just north of Cleveland) and is being bored by S & M Constructors. The system consists of several connecting tunnels, two of which are presently being bored by two Jarva machines. When completed, the system will drain storm water from the Cleveland area, outletting into Lake Erie.

One of the machines is an 18' mixed-face borer, and the other is a 14' 3" hard-rock tunneler. The mixed-face borer is expected to encounter silty sediments as it nears Lake Erie, whereas the hard-rock tunneler will remain in shale. Both machines are operating at a depth of approximately 60 feet. The muck from both machines is transported to the junction of the tunnels by trains. At the junction, which is open to the surface, a crane lifts the hoppers of the cars out of the tunnel and dumps them onto the ground. A front-end loader fills waiting trucks with the muck which is then hauled away.

Since only one machine was a hard-rock tunneler, we took a sample of approximately 150 lbs. from that machine along. The sample consists of a very weak shale which will probably show its cohesiveness in our tests.

APPENDIX II

ASSEMBLED DATA SHEETS

Location No. 1

Sample No. ____

Date July 5, 1972

Data Sheet
Big Hole Drilling Project

Location Data:

Location S. of Bloomfield, N.W. on Rt. 44, left just past river 12 miles to dirt road, right 4 miles

Owner of Tunnel Bureau of Reclamation

Drilling Contractor Fluor Utah

Person in Contact With "Joe" Sperry; Jay Terry, Safety Eng.

Tunnel Data:

Name of Tunnel Navajo Irrigation Project #3

Diameter 20' 6" with concrete to 18'

Length to Date 3.4 miles out of 3.5 miles

Best Shift about 100'

Best Day 247' Best Week - 1066'

No. of Men in Tunnel 12

Machine Data:

Machine Name and No. Dresser

Horsepower 700 hp. D.C.

Type of Cutter 36 double

Rotation Speed 5-8 rpm

Thrust Against Face 1,090,000 lb. - 612,000 lb.

Thrust Cylinder Diameter 4 @ 11" ea.

Water Spray? No Amount ____ Type ____

Rate of Advance 3"/min. = 15'/hr.

Size of Conveyor Belt 30"

Rock Data:

Approx. Amt. of Sample 1100 lb.

Core Available? No

Present Type of Rock Sandstone with a shale layer

Compressive Strength Very weak

Other Comments:

Location No. ____________

Sample No. ____________

Date July 10, 1972

Data Sheet
Big Hole Drilling Project

Location Data:

Location Rt. 64, White Pine, Michigan

Owner of Tunnel White Pine

Drilling Contractor White Pine Copper Company

Person in Contact With Cliff Hanninen - Mine Research

Jack Sipola - Boring Supt.

Tunnel Data:

Name of Tunnel ____________

Diameter 18' 2"

Length to Date 7000 ft. out of 2 miles

Best Shift 24'

Best Day 44'

No. of Men in Tunnel 6

Machine Data:

Machine Name and No. Robbins 181-122

Horsepower 4 200 hp.

Type of Cutter 47 disc

Rotation Speed 4 1/2 rpm

Thrust Against Face 1,250,000 lb.

Thrust Cylinder Diameter 4 at 12" 2700 psi

Water Spray? Yes Amount ? Type 11 nozzels

Rate of Advance 5 1/2' hr.

Size of Conveyor Belt 30" on machine, 36" main line

Rock Data:

Approx. Amt. of Sample 100 lbs.

Core Available? No

Present Type of Rock Nonesuch shale

Compressive Strength ____________

Other Comments:

____

____

____

Location No. ______________

Sample No. ______________

Date ______________

Data Sheet
Big Hole Drilling Project

Location Data:

Location: Euclid, Ohio

Owner of Tunnel: City of Euclid

Drilling Contractor: S & M Constructors

Person in Contact With: Ed Norman & Dick Stier

Tunnel Data:

Name of Tunnel: Moss Point Drainage System

Diameter: 14' 3"

Length to Date: 1976 out of 3800

Best Shift: 30

Best Day: 77 272 for 5 days

No. of Men in Tunnel: 12

Machine Data:

Machine Name and No.: Jarva Mark 12-1403

Horsepower: 500 on 4 motors 125 each

Type of Cutter: Reed QK multiple disc

Rotation Speed: 10.75 rpm

Thrust Against Face: 1,134,000 lb.

Thrust Cylinder Diameter: ?

Water Spray? Yes Amount 5 gpm Type Water only

Rate of Advance: 12 ft./hr.

Size of Conveyor Belt: 24 on mach., 18 trailing

Rock Data:

Approx. Amt. of Sample: 175 lb.

Core Available? No

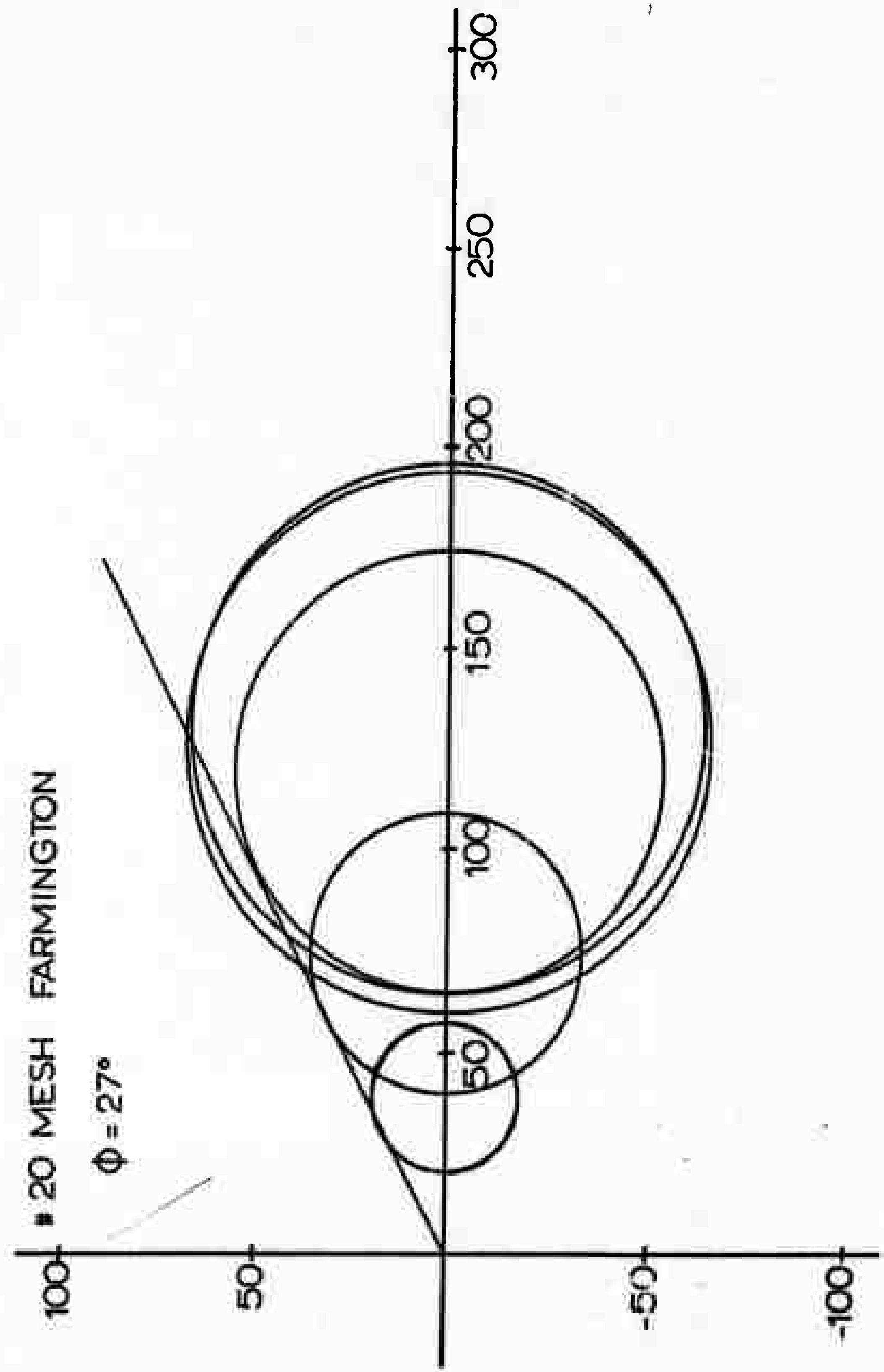
Present Type of Rock: Shale

Compressive Strength: Weak - 1500-2000 psi

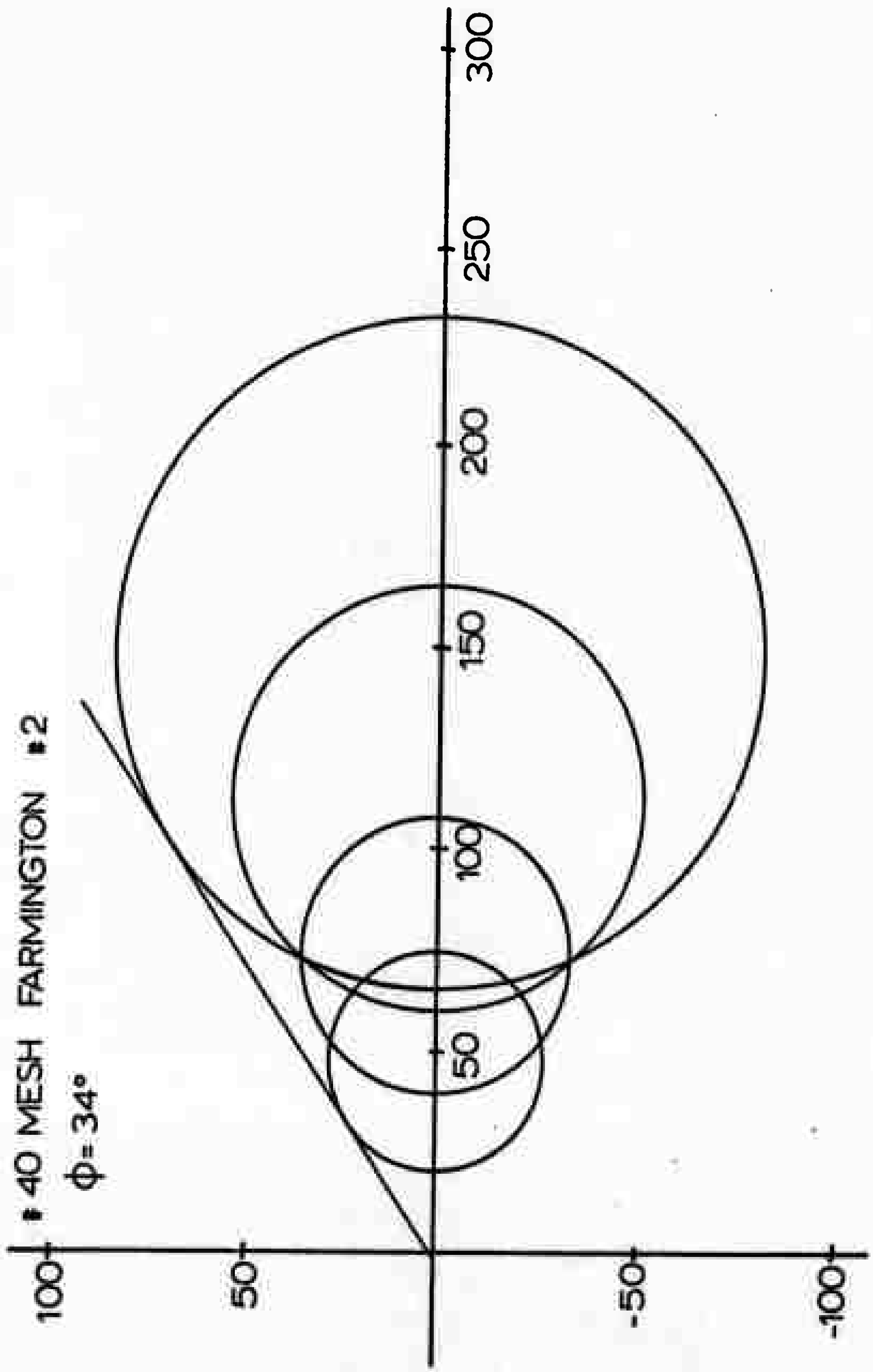
Other Comments:

APPENDIX III

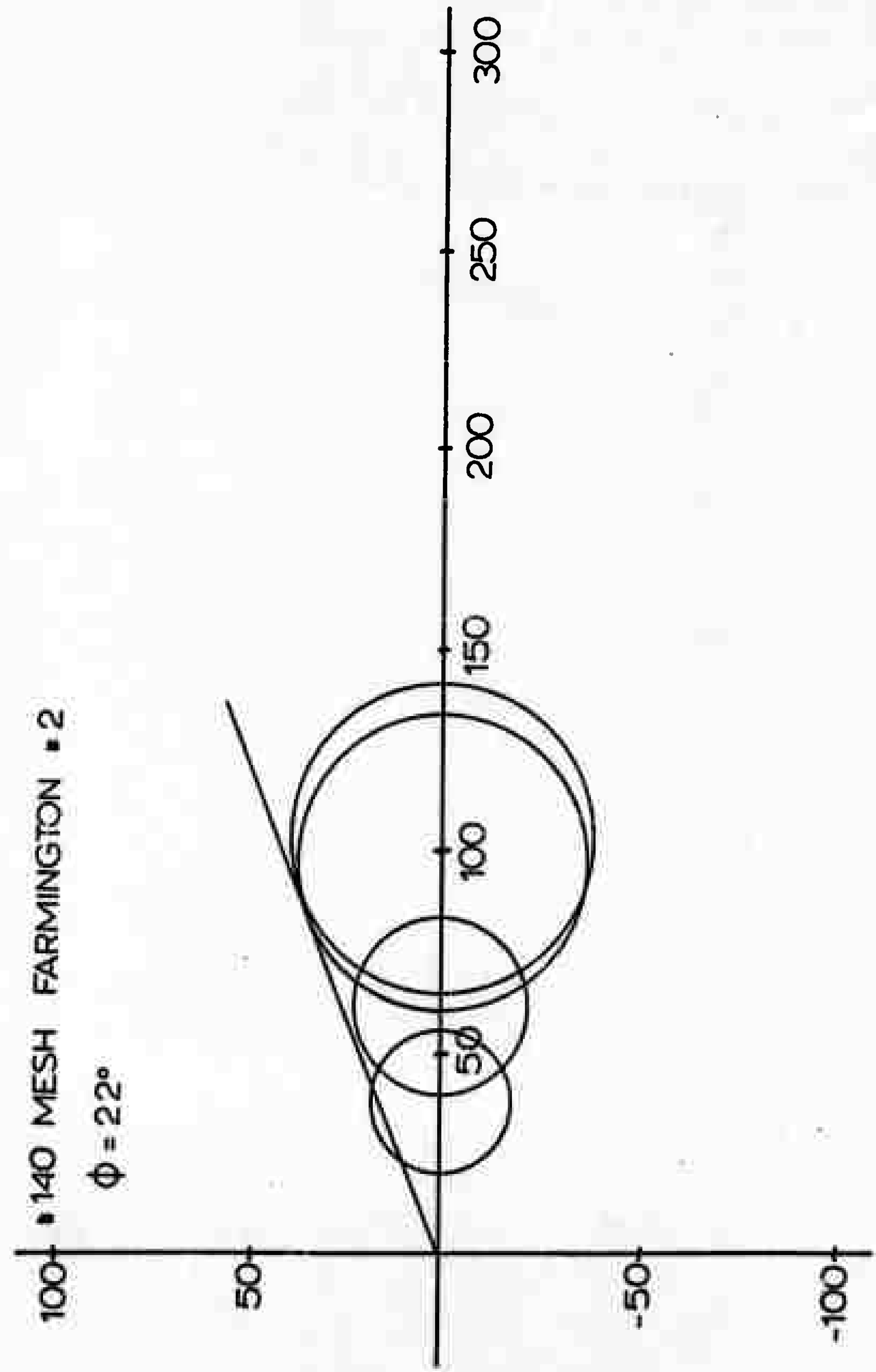
MOHR'S ENVELOPE FOR EACH SAMPLE



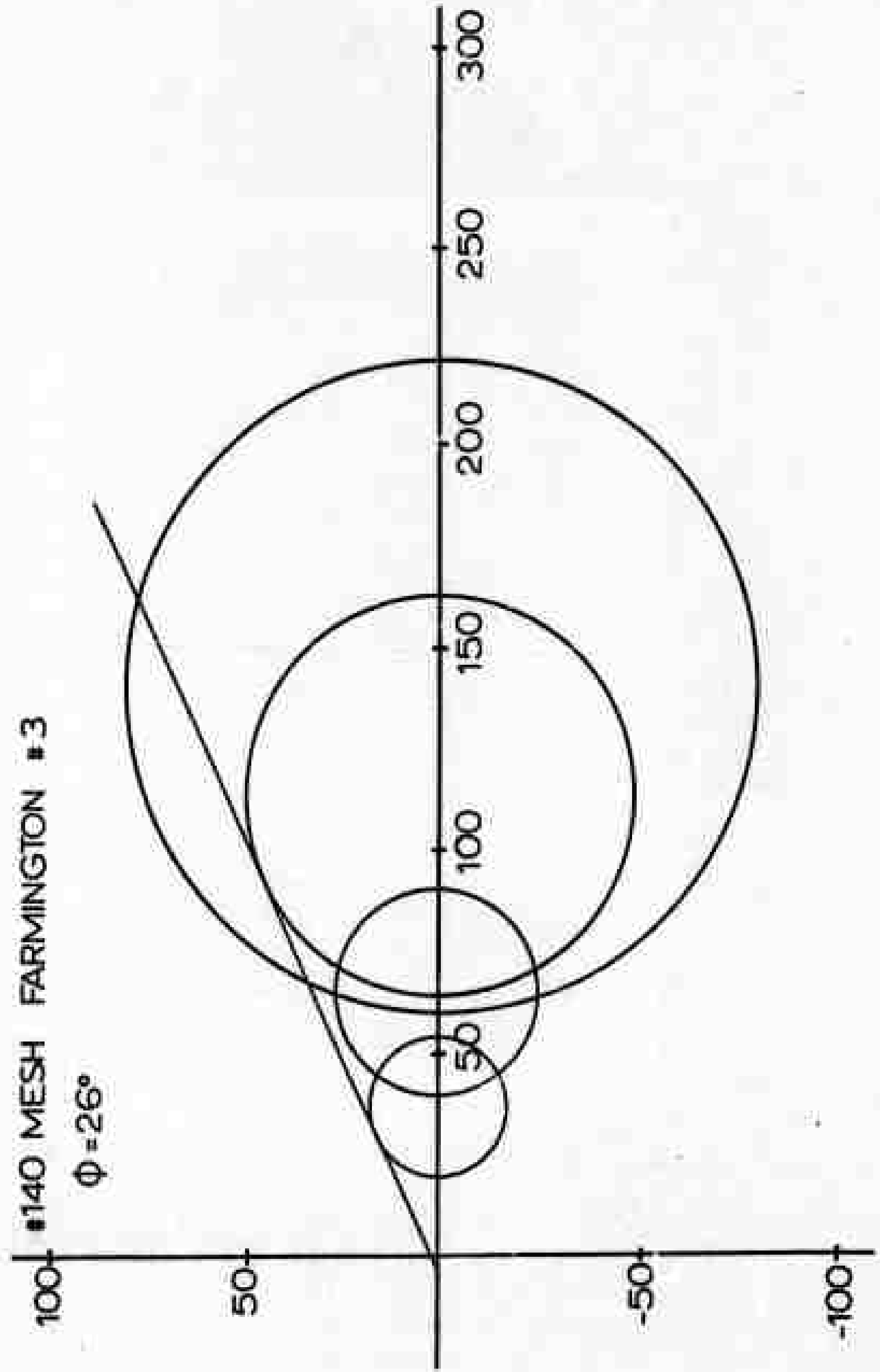
20 MESH FARMINGTON
Φ = 27°
100
50
-50
-100
50
100
150
200
250
300

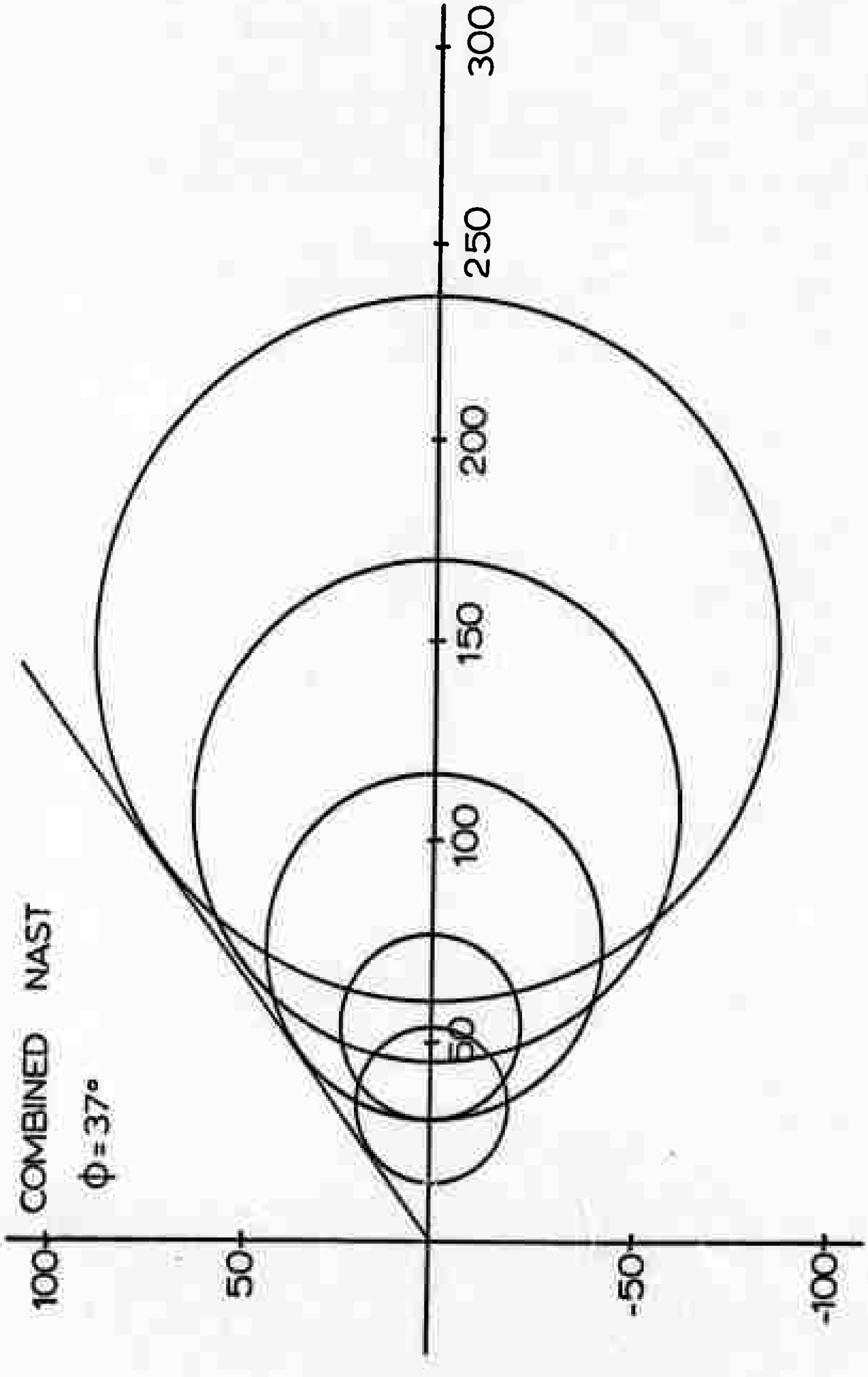


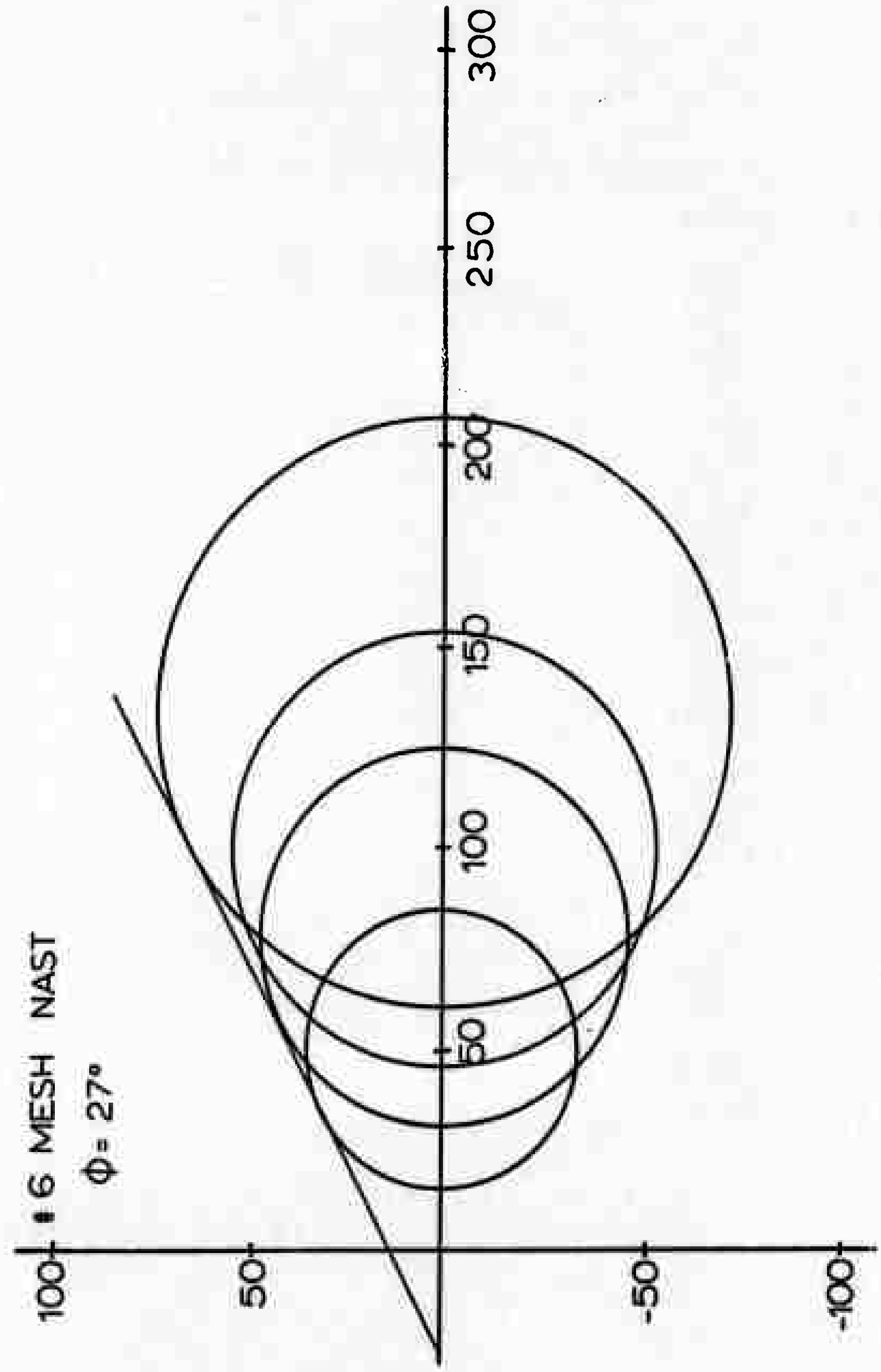
40 MESH FARMINGTON #2
φ= 34°
50
100
150
200
250
300
100
50
-50
-100



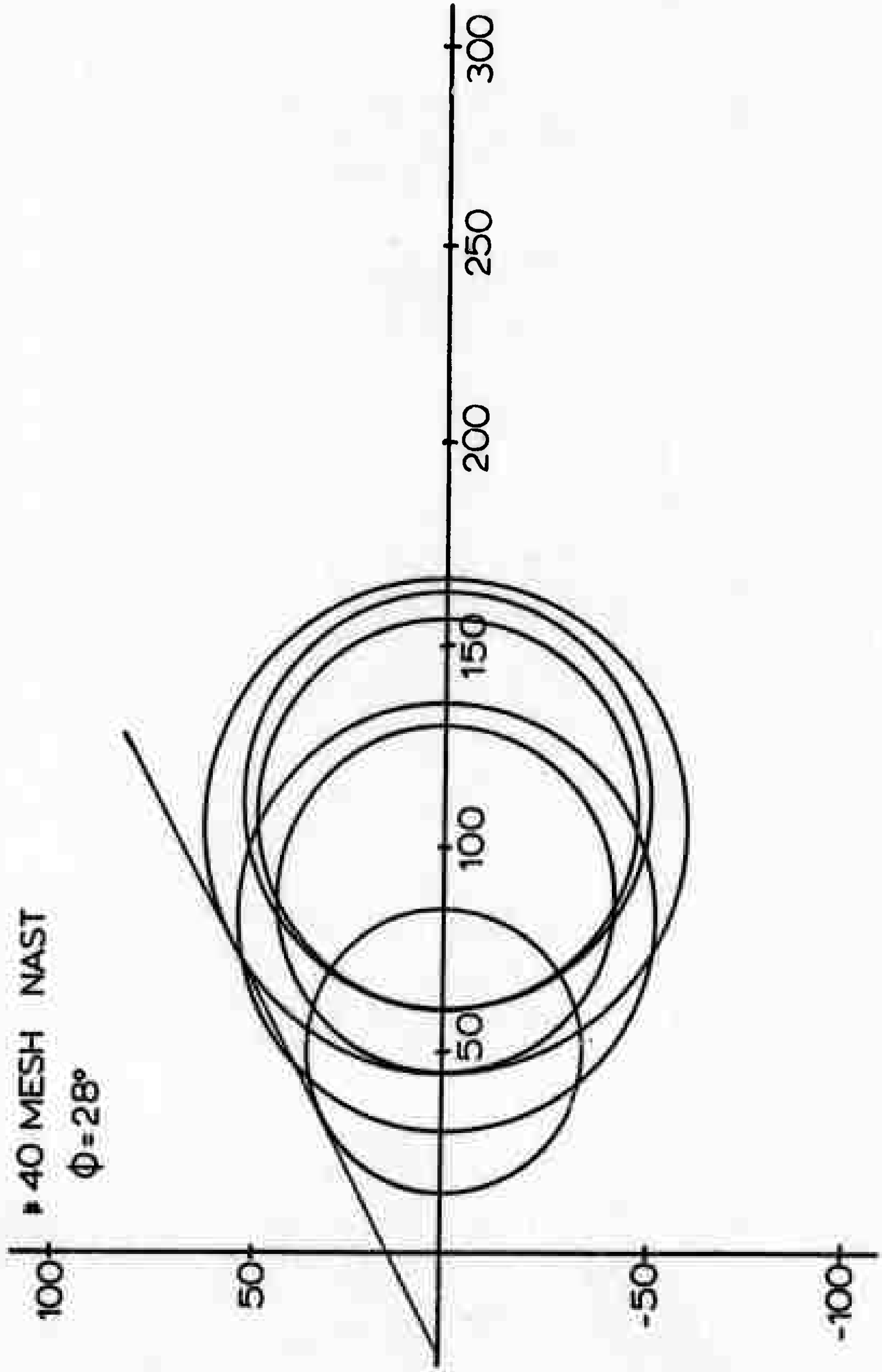
#140 MESH FARMINGTON #2
φ = 22°
100
50
-50
-100
50
100
150
200
250
300


#140 MESH FARMINGTON #3
Φ = 26°
50
100
150
200
250
300
100
50
-50
-100

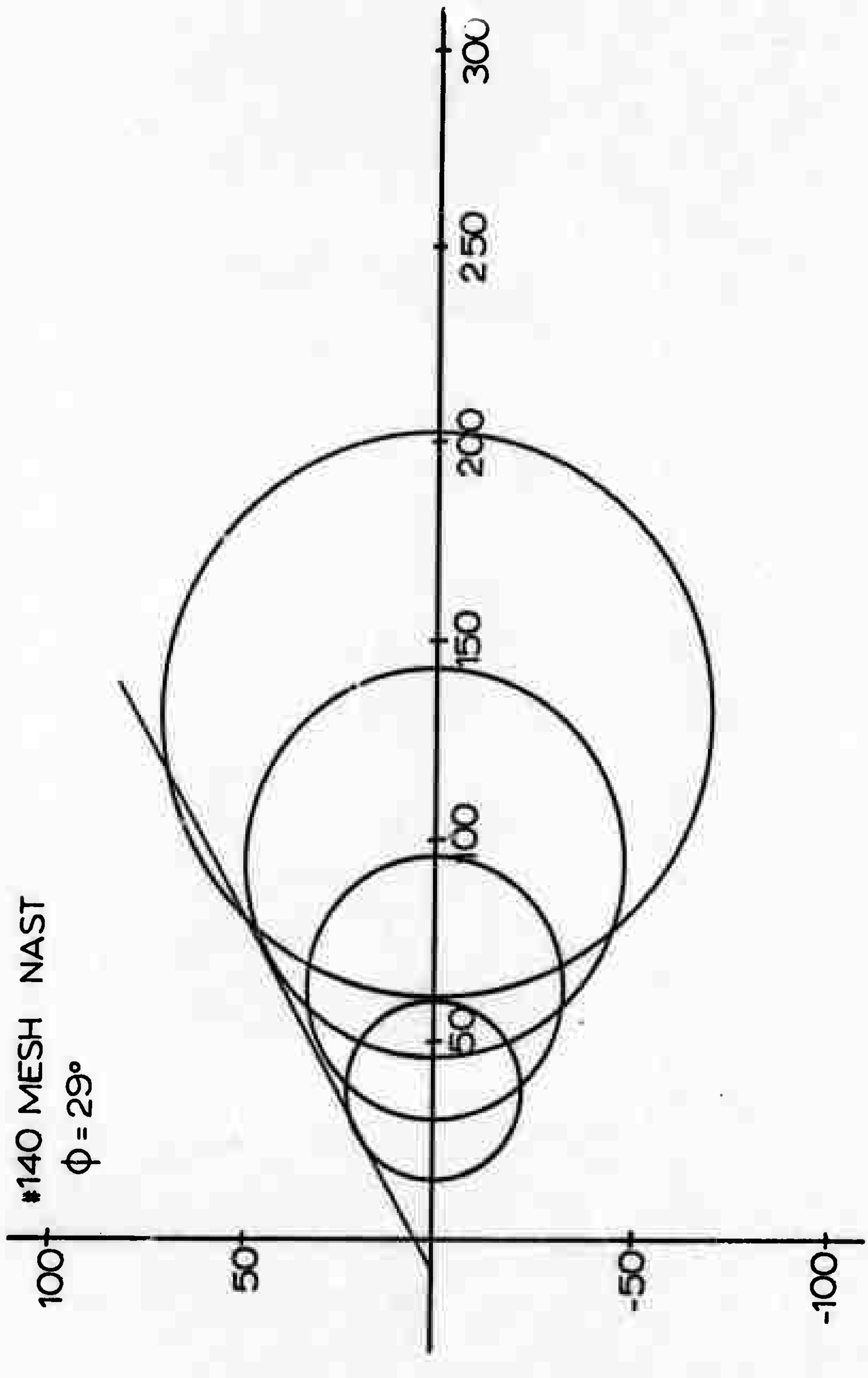

COMBINED NAST
φ=37°
100
50
-50
-100
50
100
150
200
250
300

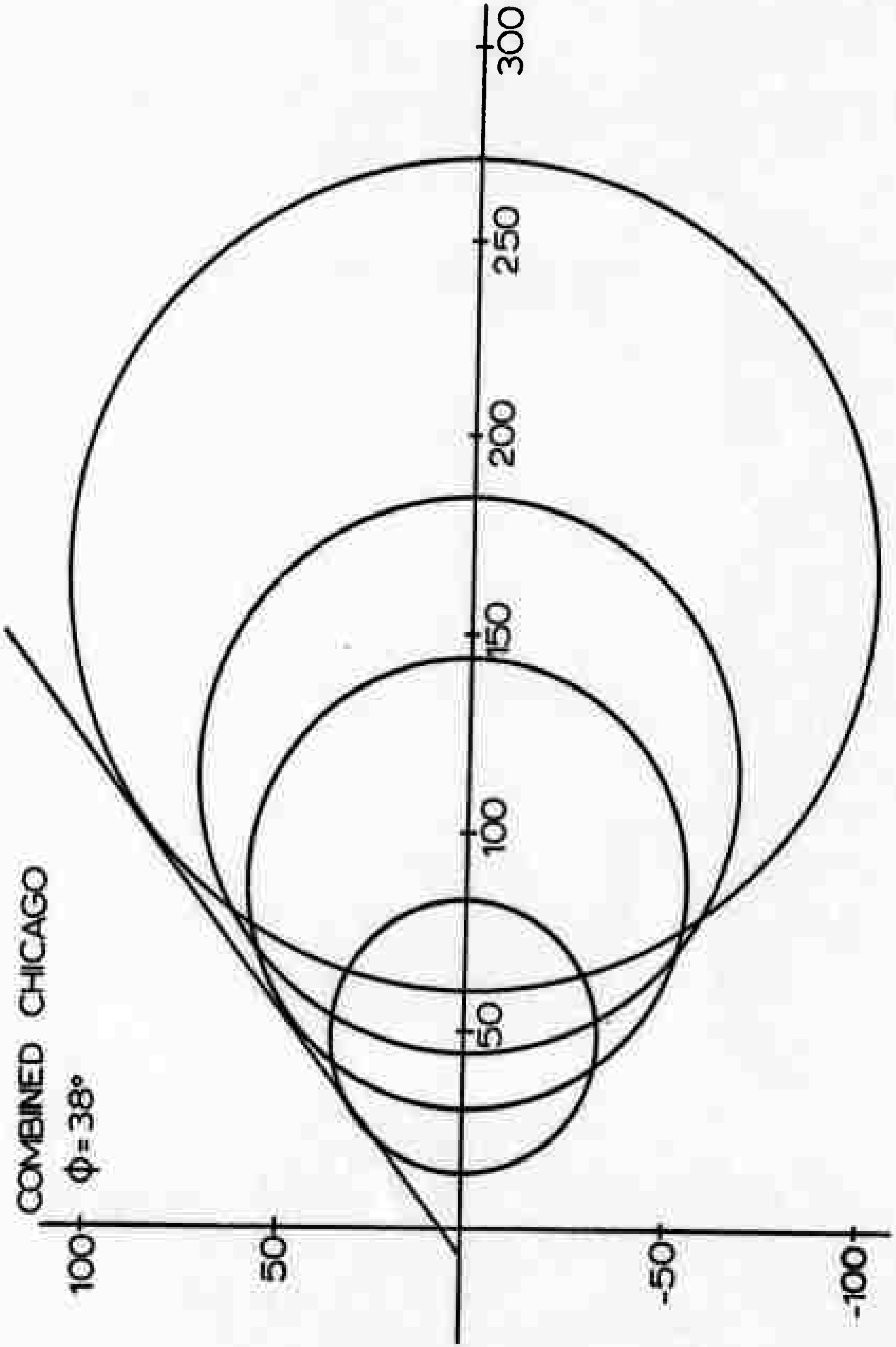


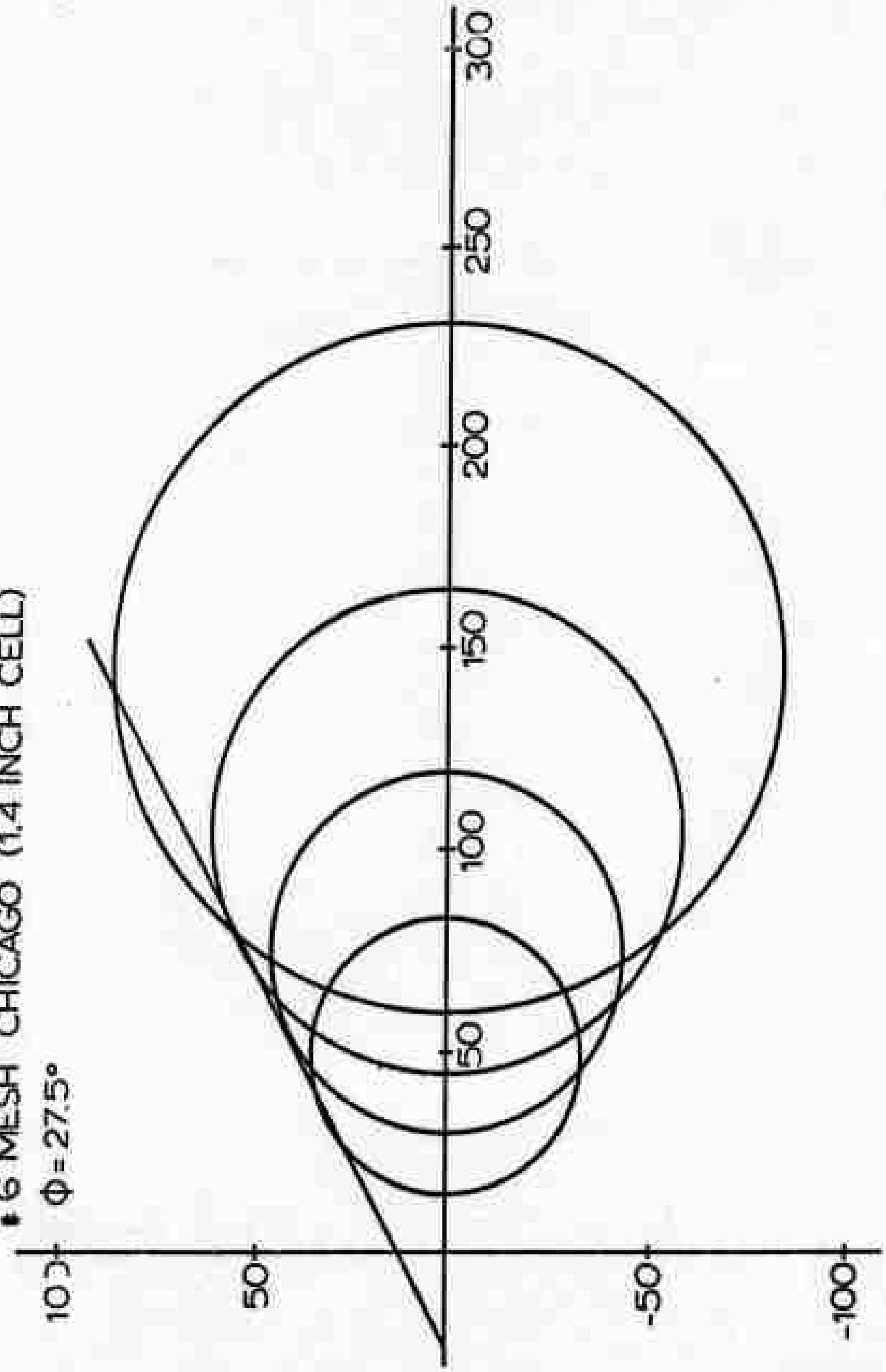
6 MESH NAST
Φ = 27°
100
50
-50
-100
50
100
150
200
250
300

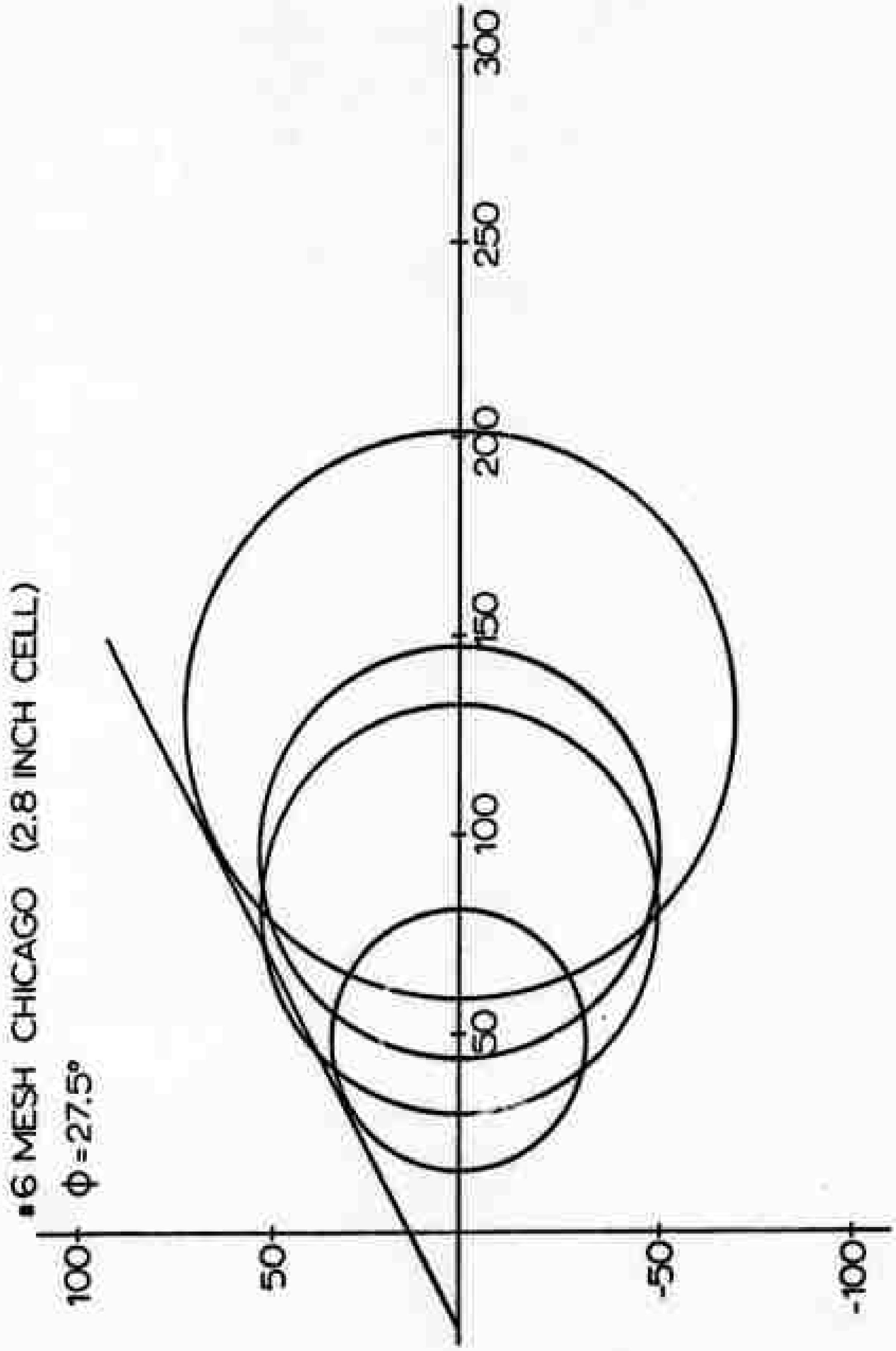


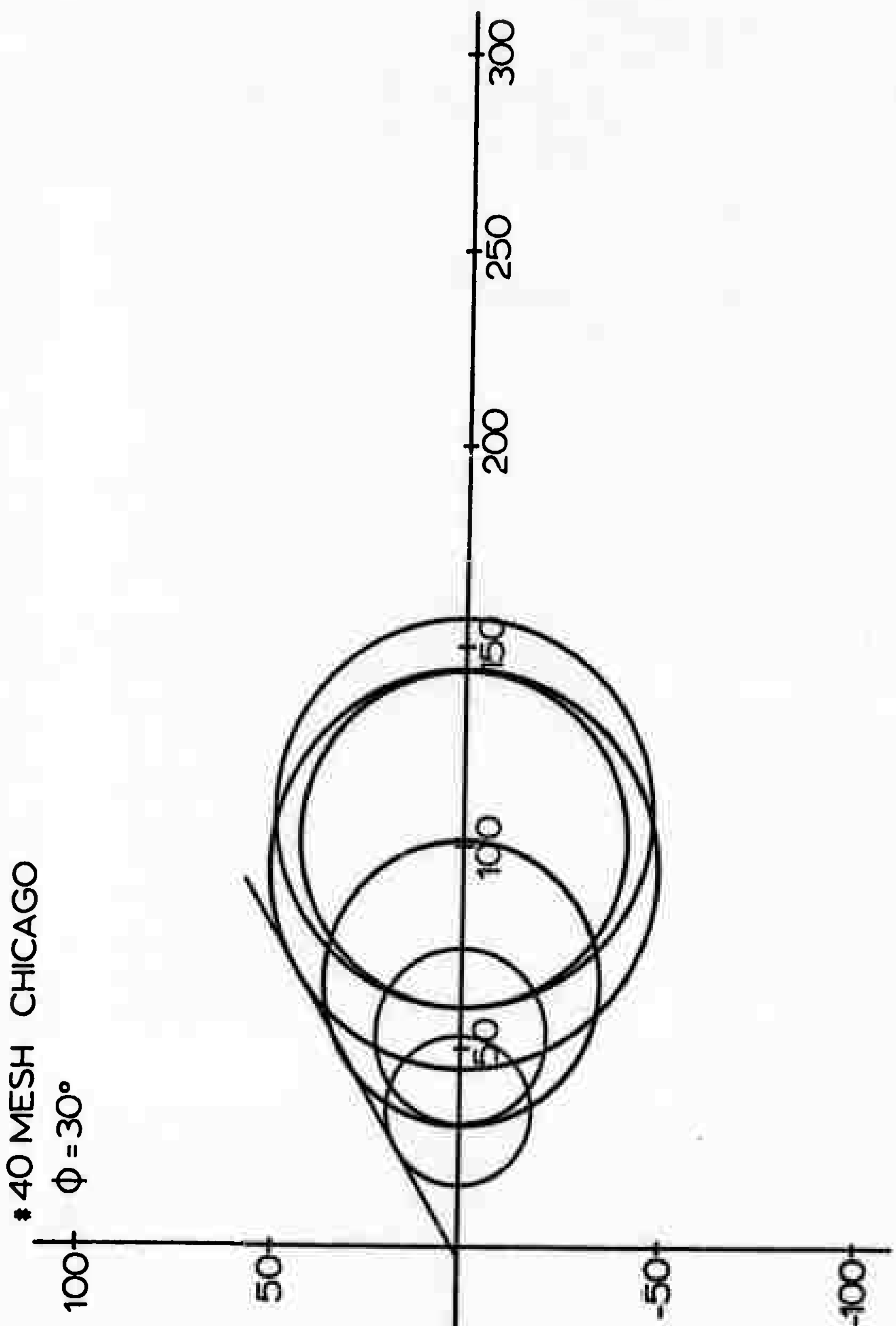
40 MESH NAST
Φ=28°
50
100
150
200
250
300
100
50
-50
-100

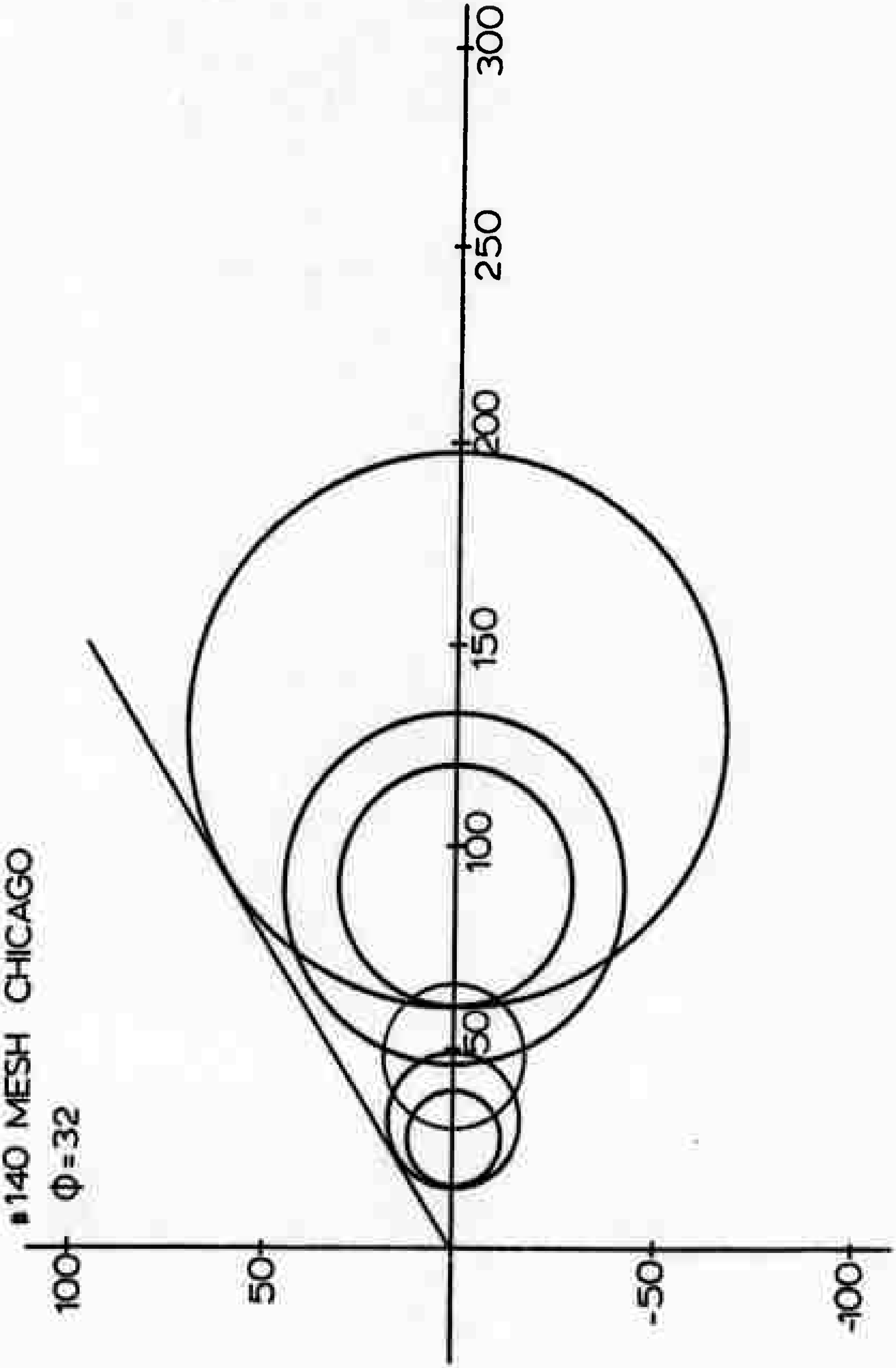

#140 MESH NAST
φ = 29°
100
50
-50
-100
50
100
150
200
250
300

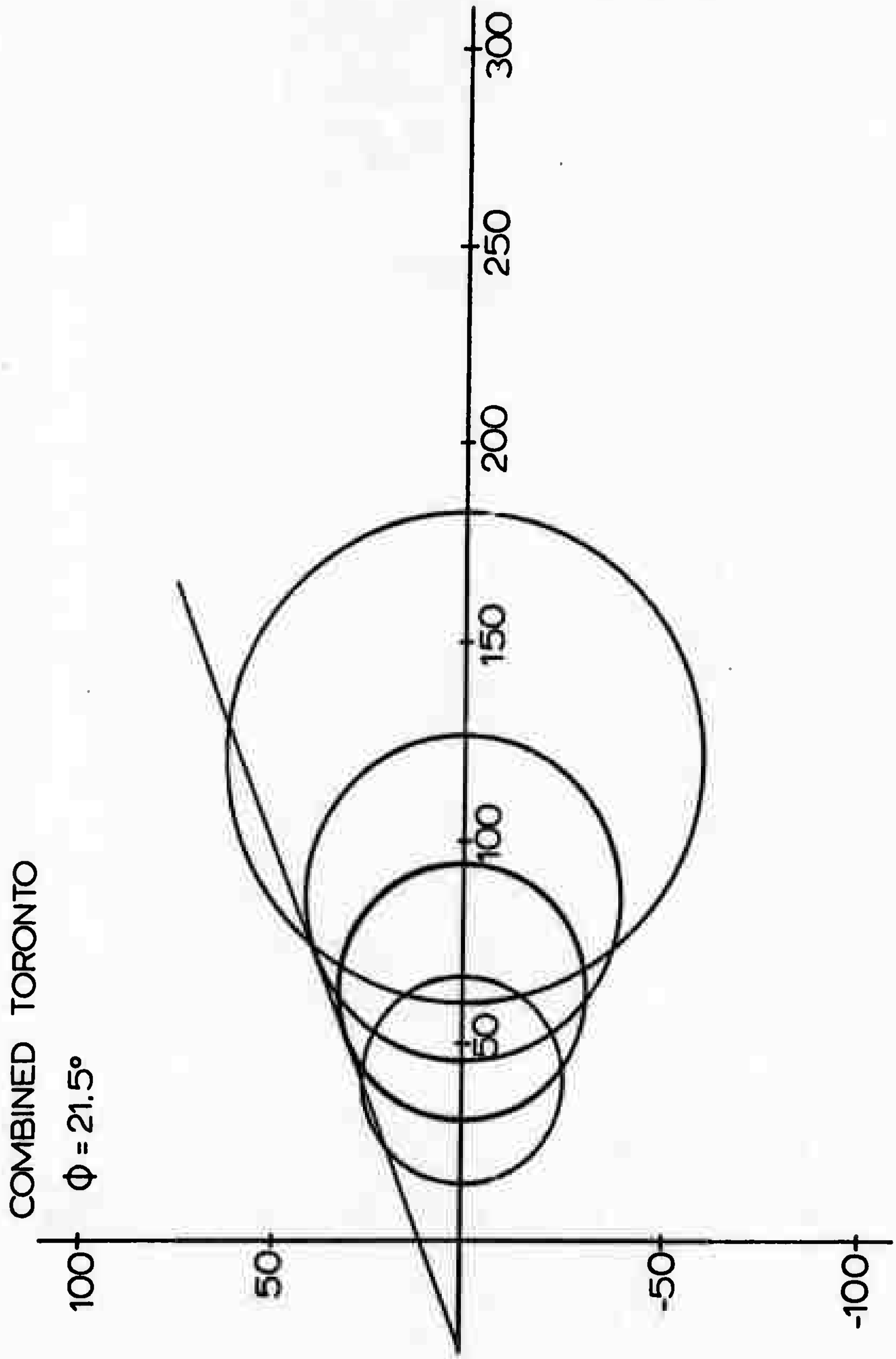

COMBINED CHICAGO
φ = 38°
100
50
-50
-100
50
100
150
200
250
300

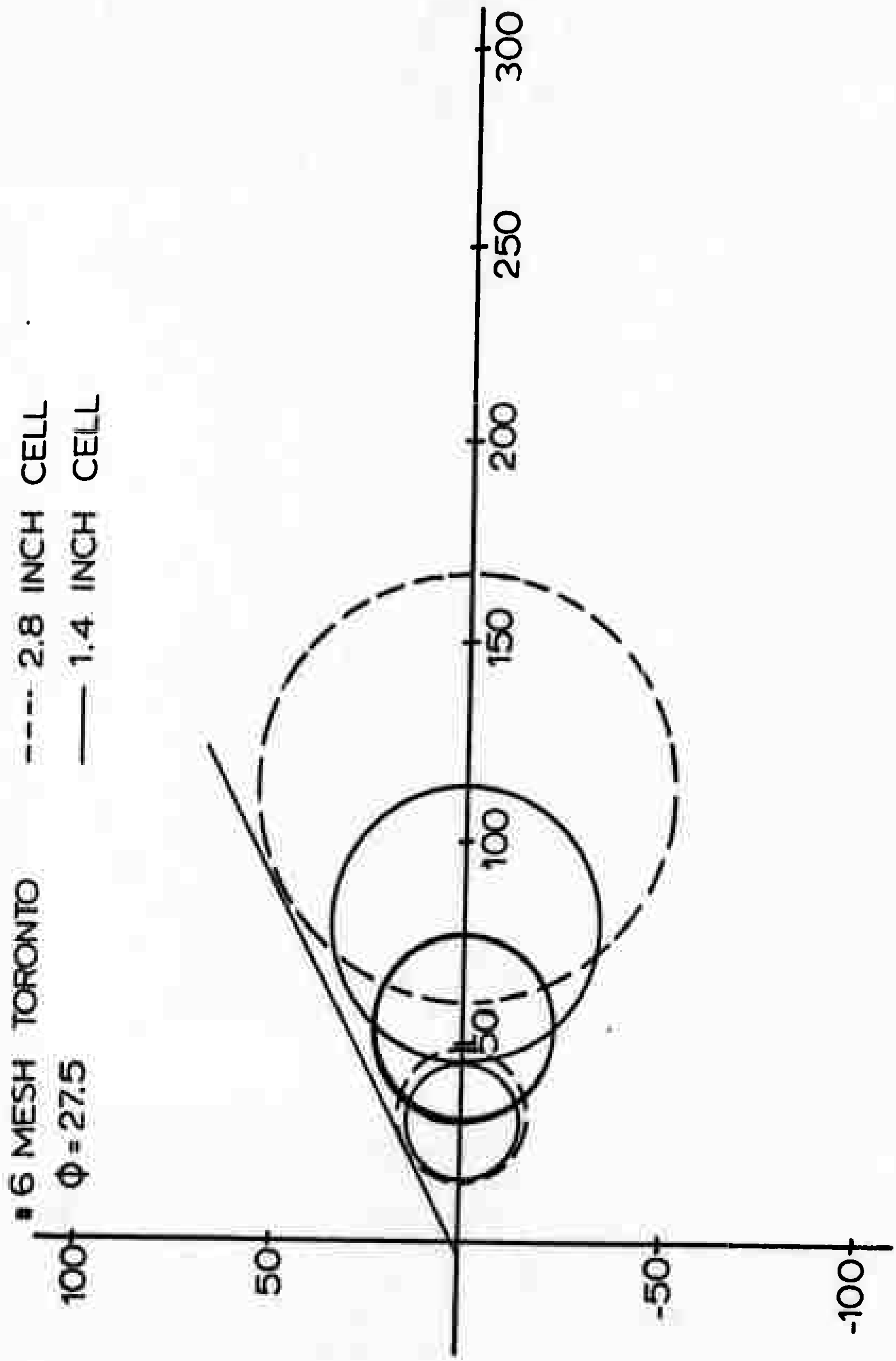

• 6 MESH CHICAGO (1.4 INCH CELL)
Φ = 27.5°
50
100
150
200
250
300
100
50
-50
-100

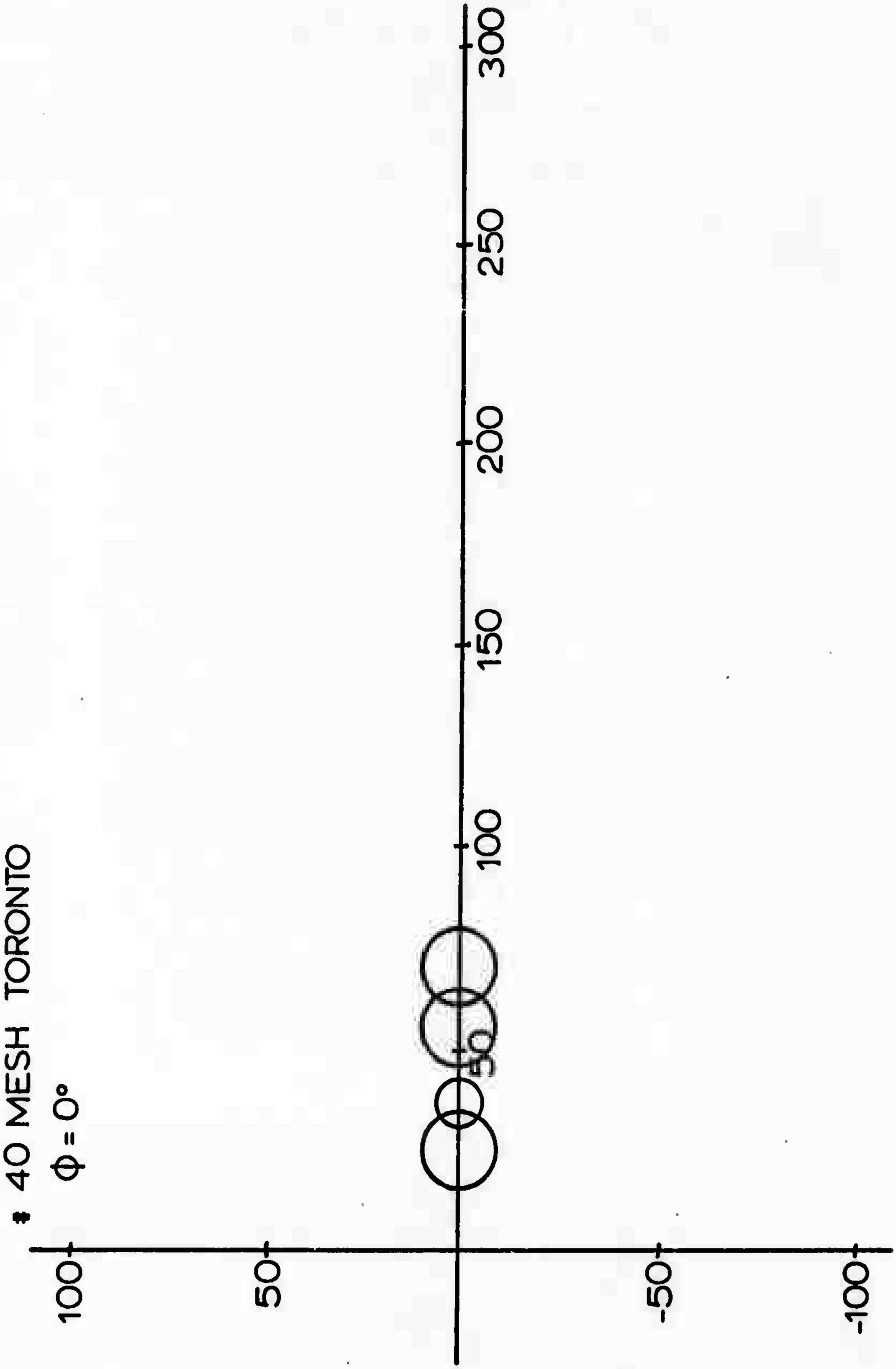

#6 MESH CHICAGO (2.8 INCH CELL)
φ = 27.5°
100
50
-50
-100
50
100
150
200
250
300


#40 MESH CHICAGO
Φ = 30°
100
50
-50
-100
50
100
150
200
250
300

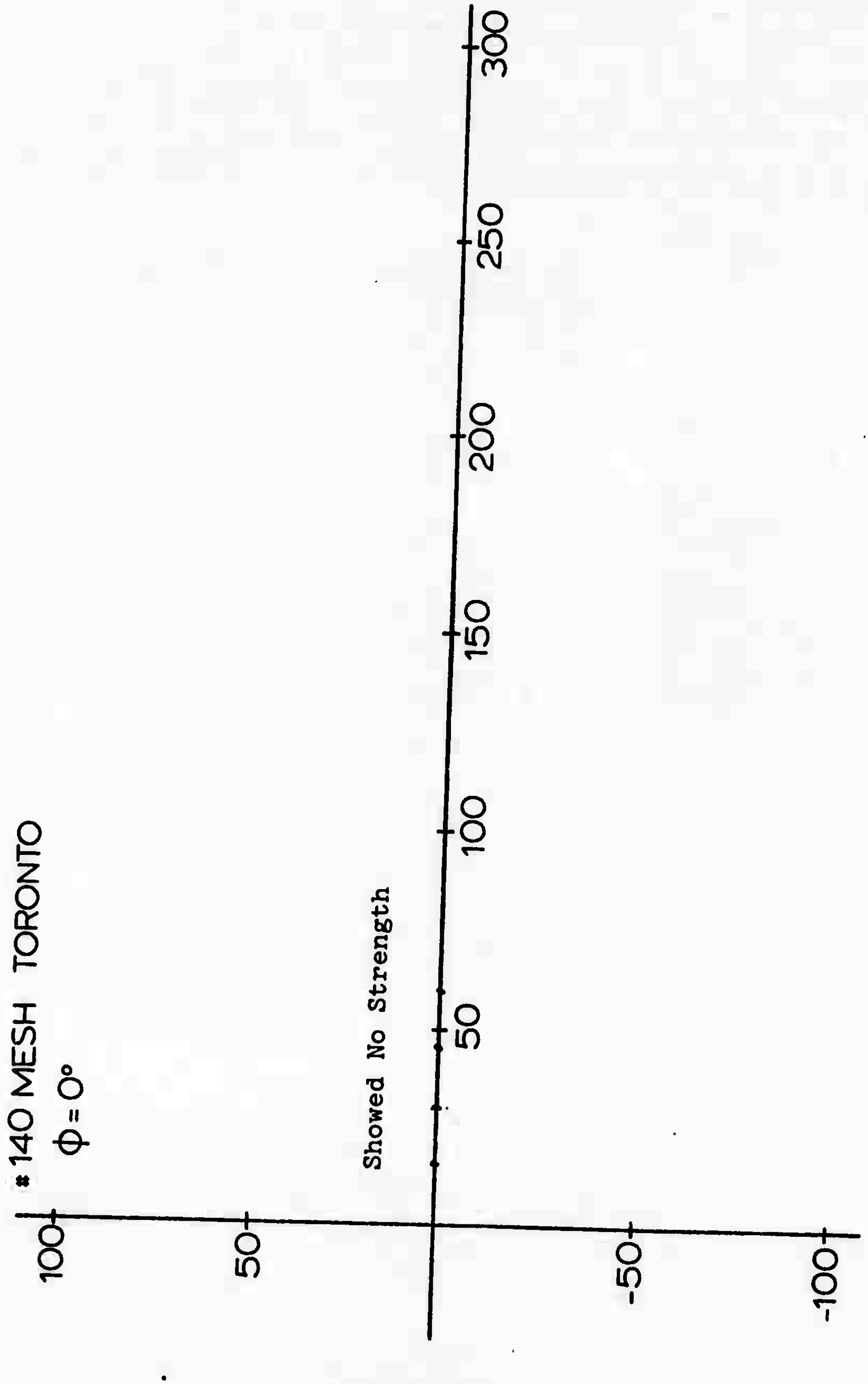

#140 MESH CHICAGO
Φ=32
100
50
-50
-100
50
100
150
200
250
300


COMBINED TORONTO
$\Phi = 21.5°$
50
100
150
200
250
300
100
50
-50
-100

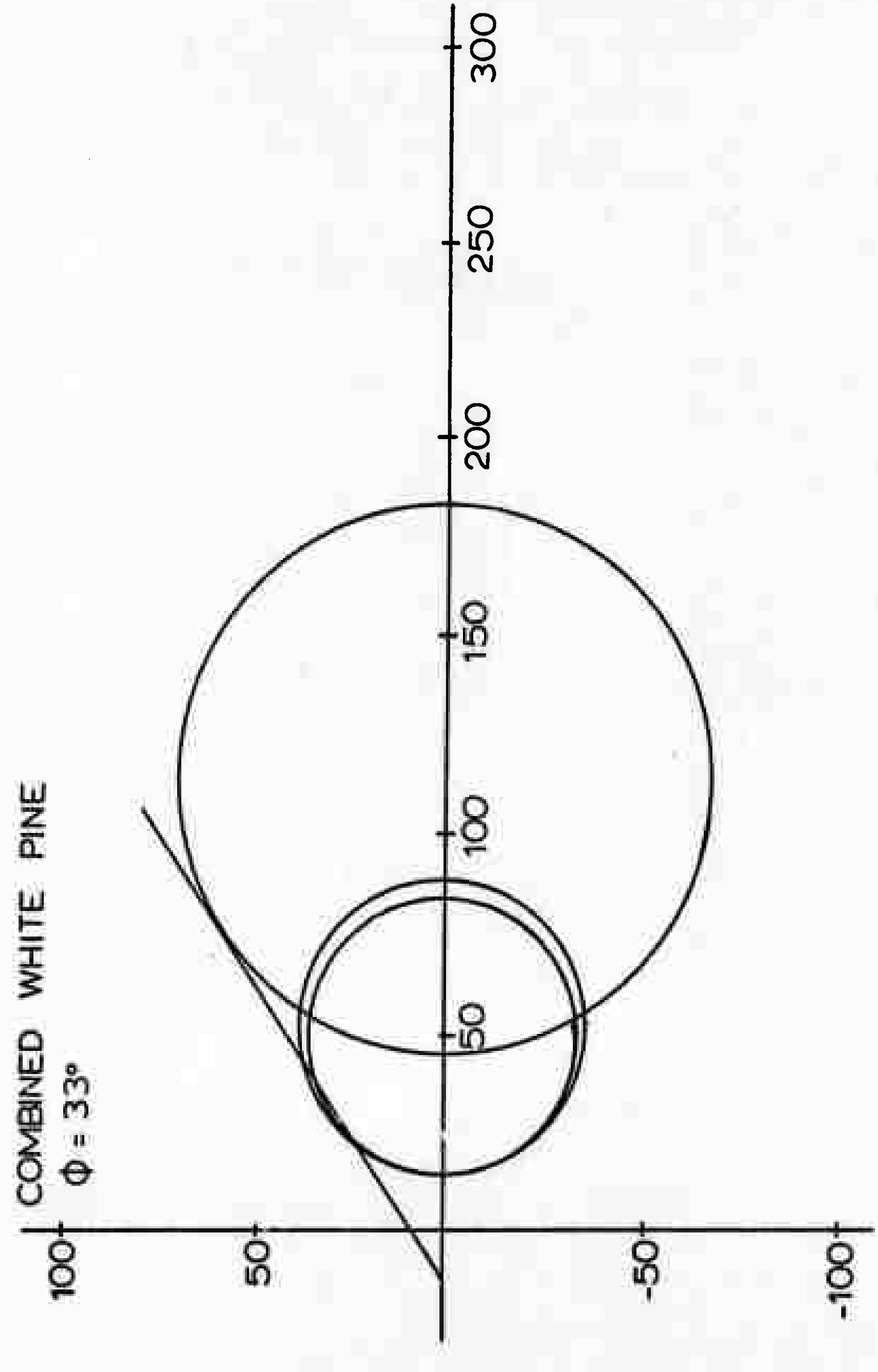

#6 MESH TORONTO
Φ = 27.5
2.8 INCH CELL
1.4 INCH CELL
100
50
-50
-100
50
100
150
200
250
300

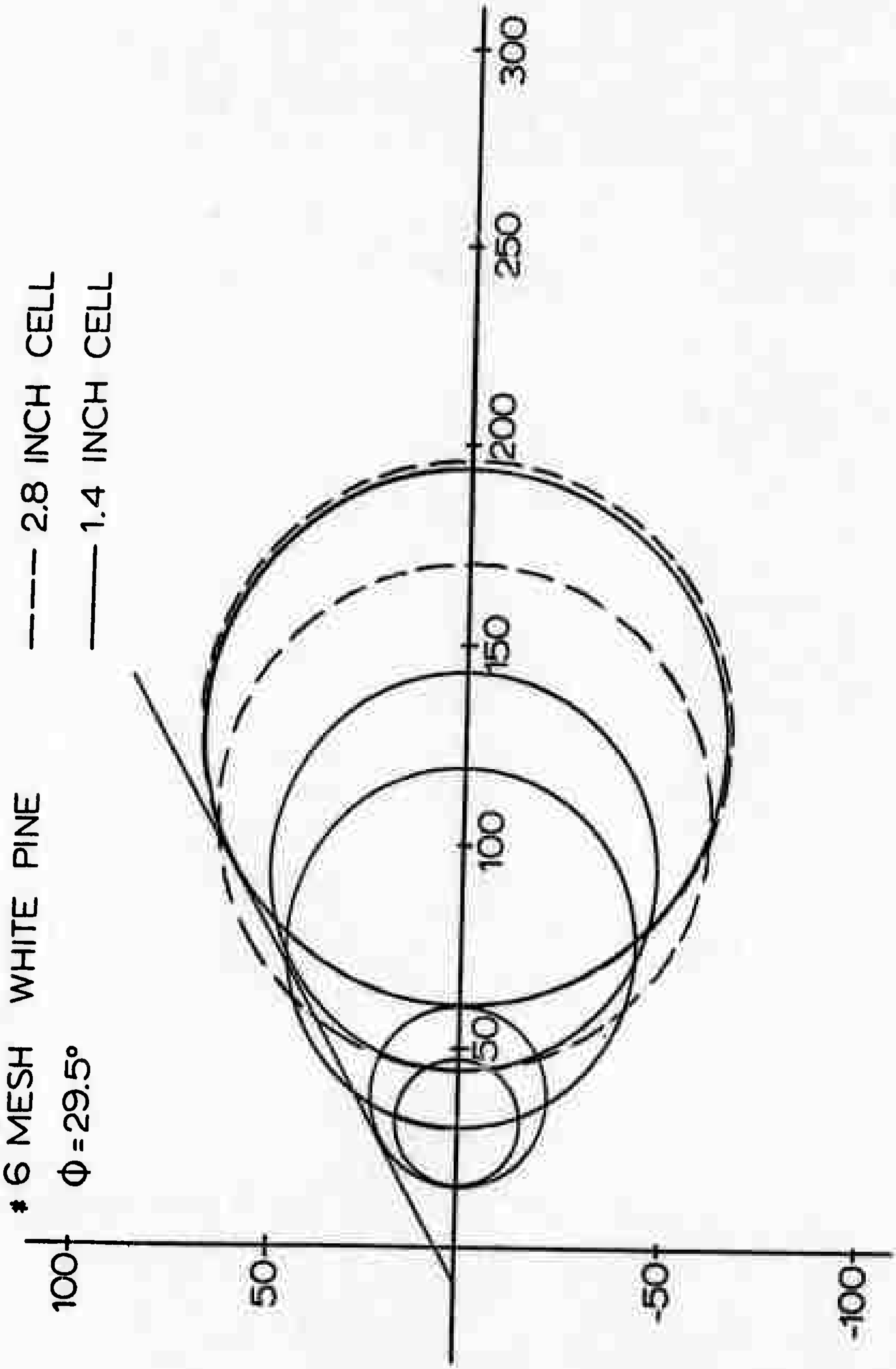


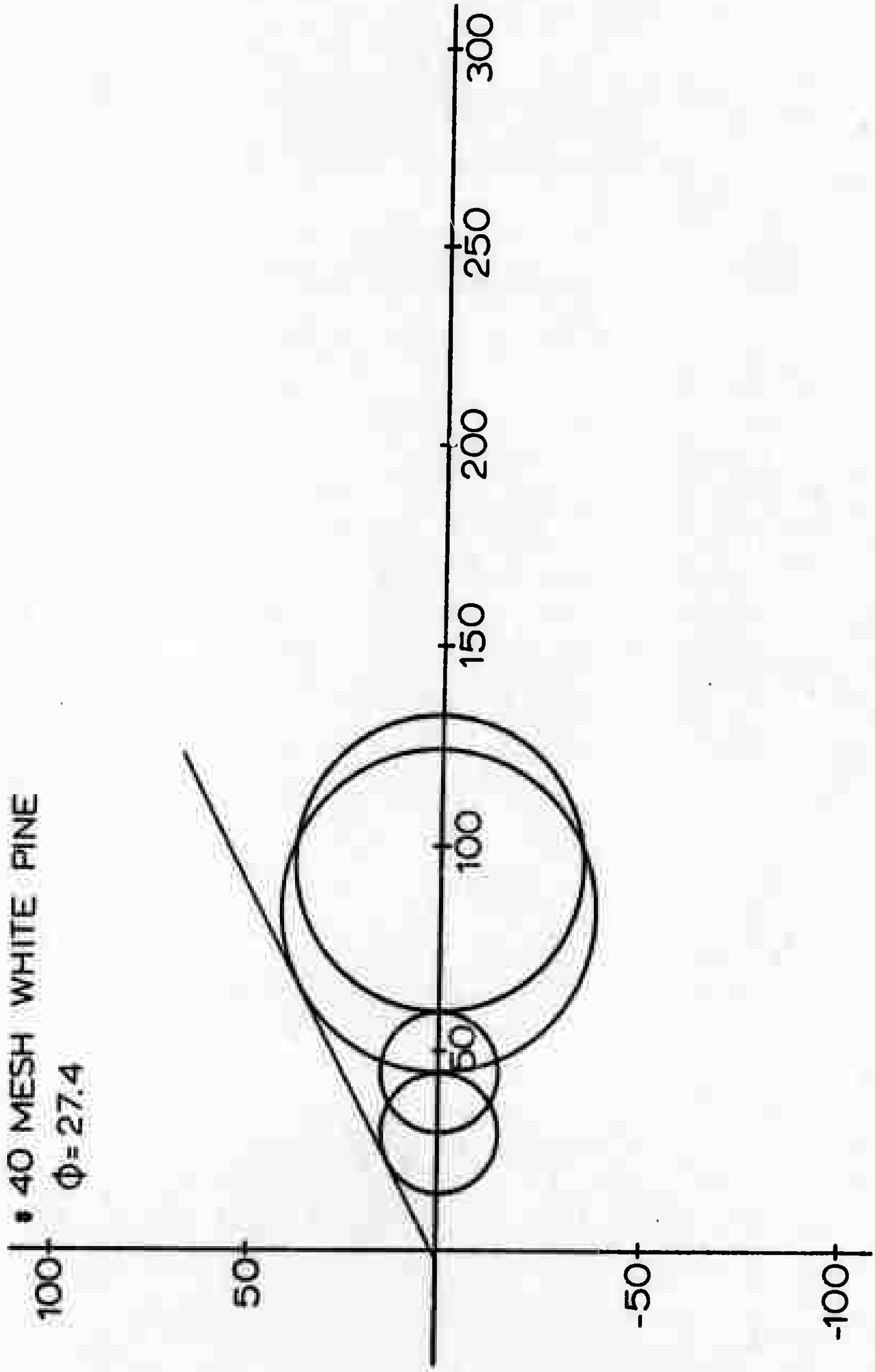
40 MESH TORONTO
Φ = 0°
100
50
-50
-100
50
100
150
200
250
300

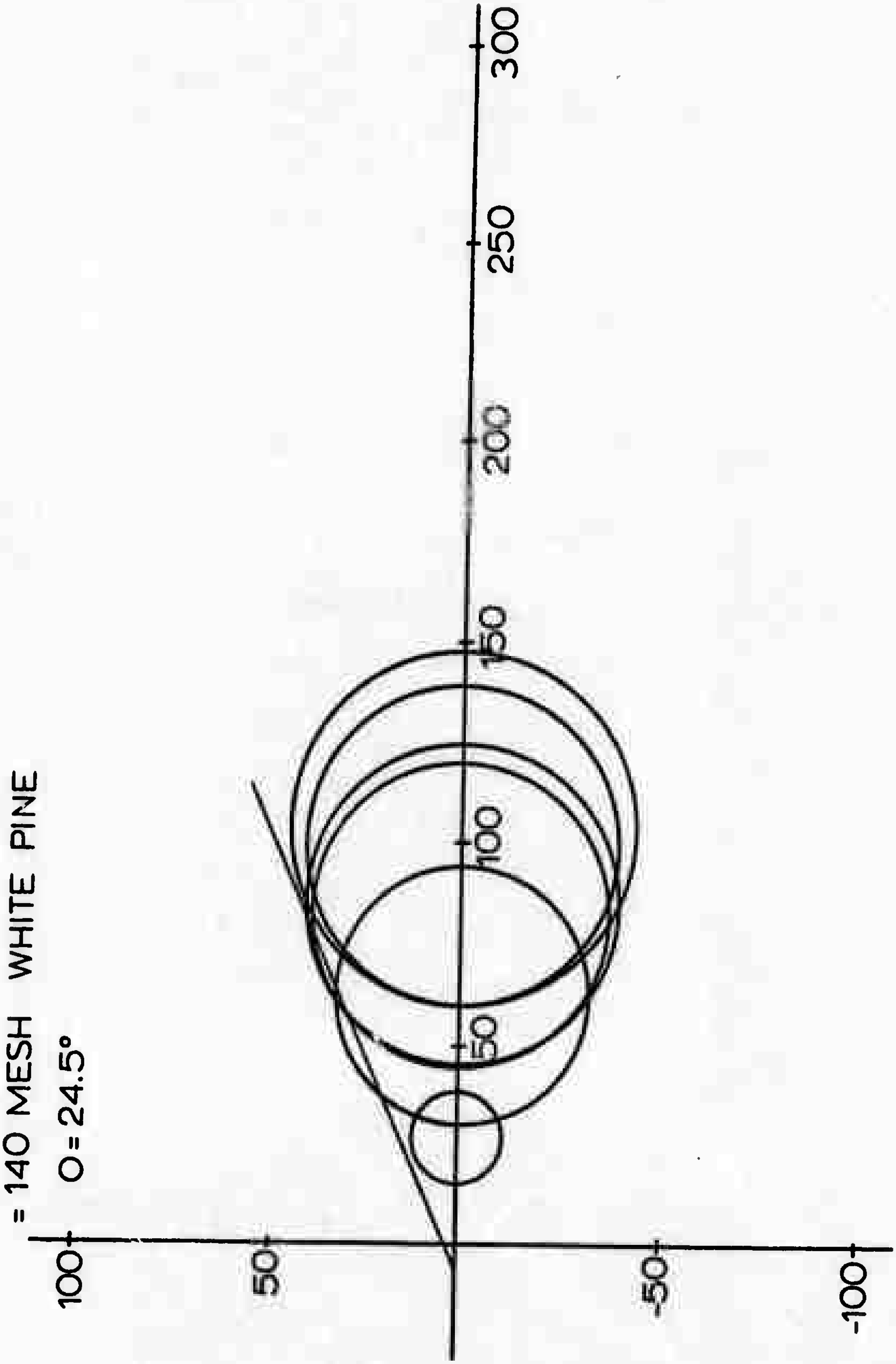


140 MESH TORONTO
Φ = 0°
Showed No Strength
100
50
-50
-100
50
100
150
200
250
300


COMBINED WHITE PINE
Φ = 33°
50
100
150
200
250
300
100
50
-50
-100


* 6 MESH WHITE PINE
Φ = 29.5°
2.8 INCH CELL
1.4 INCH CELL
100
50
-50
-100
50
100
150
200
250
300


• 40 MESH WHITE PINE
Φ=27.4
100
50
-50
-100
50
100
150
200
250
300


= 140 MESH WHITE PINE
O= 24.5°
50
100
150
200
250
300
100
50
-50
-100

APPENDIX IV

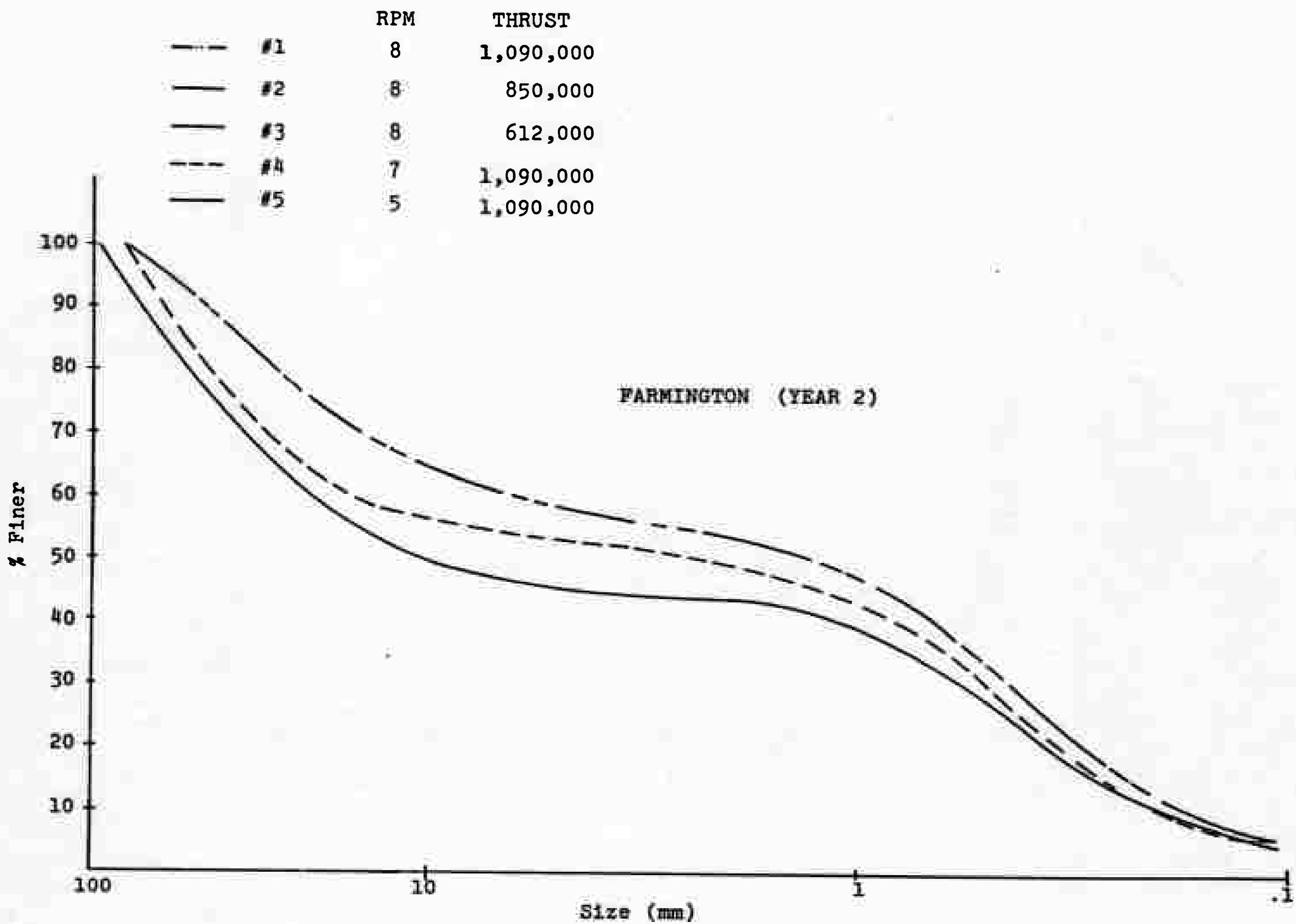
TABLE OF MOHR'S CIRCLE DATA

Location:	Farmington		Nast		Chicago		Toronto		White Pine	
Particle Size:	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3
Combined			15	54	15	82	15	66	15	83
			30	78	30	145	30	95	15	91
			30	118	45	185	45	138	45	186
			45	170	60	270	60	183		
			60	238						
#6 Mesh			15	86	15	85	15	45	15	48
			30	125	30	120	15*	49	15*	60
			45	154	45	166	30	78	30	120
			60	208	60	232	45	115	45	145
					15*	82	60*	169	45*	170
					30*	135			60	195
					45*	149			60*	197
					60*	205				
#20 Mesh	20	58								
	40	110								
	60	195								
	65	175								
	65	197								
#40 Mesh	20	75	15	85	15	52	15	35	15	45
	40	108	30	135	30	75	30	42	30	60
	60	165	45	130	30	102	45	65	45	125
	65	233	45	168	45	145	60	80	60	135
			60	158	60	144				
			60	165	60	158				
#140 Mesh	20	55	15	60	15	39	15	15	15	40
	40	85	30	96	15	49	30	30	30	96
	60	134	45	145	30	66	45	45	45	121
	65	142	60	205	45	133	60	60	45	126
					60	121			60	141
					60	200			60	149

*2.8-inch cell

APPENDIX V

GRADATION OF SAMPLES


RPM THRUST
#1 8 1,090,000
#2 8 850,000
#3 8 612,000
#4 7 1,090,000
#5 5 1,090,000
FARMINGTON (YEAR 2)
% Finer
100
90
80
70
60
50
40
30
20
10
100
10
1
.1
Size (mm)

White Pine